SATELLITE SERVICING

A NASA REPORT TO CONGRESS

NASA OFFICE OF SPACE FLIGHT

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Preface

Satellite Servicing, A Report to Congress has been compiled by the National Aeronautics and Space Administration in response to a request from the Congress to *"... conduct a thorough and comprehensive study of satellite servicing with a view toward establishing national goals and objectives for utilizing such capabilities."* Section 118 of the National Aeronautics and Space Administration Authorization Act of 1988 (H.R. 2782) stipulates that *"... the capital investment in space satellites and vehicles should be enhanced and protected by establishing a system of servicing, rehabilitation, and repair capabilities in orbit (hereinafter referred to as 'satellite servicing')."*

Satellite Servicing is recognized within NASA as an evolving capability currently in an early stage of development, a fact reflected in the compilation of this document. With this understanding, NASA addresses those major elements of the Act identified in the Congressional Request. The seven elements are listed below in the order in which they appear in the report.

- *Experience to date with on-orbit satellite servicing including the costs of such operations and the fees charged to non-NASA users;*

- *The use of the Shuttle, the Station, and other space vehicles to carry out or support satellite servicing;*

- *The pertinence of satellite servicing to satellite and vehicle design;*

- *The pertinence of satellite servicing to NASA and other space programs, including science and applications programs;*

- *All potential users of satellite servicing capabilities, including civilian, defense, private, and foreign satellites and space vehicles;*

- *The pertinence of satellite servicing to insurance, including the character, cost, and availability of insurance; and*

- *The prices to be charged for satellite servicing such that the full costs of such servicing can be recovered.*

NASA intends that this report shall inform the reader as completely and comprehensively as possible regarding the current scope of satellite servicing, provide definitive examples of capability, and address future requirements. Within this context, overall NASA goals and objectives for the utilization of satellite servicing capabilities are presented as candidates for national civil goals and objectives.

Acknowledgement

NASA's Office of Space Flight gratefully acknowledges the assistance of the NASA Satellite Servicing Steering Committee and Working Groups' representatives (the Office of the Comptroller, Space Science and Applications, Aeronautics and Space Technology, Space Station, Commercial Programs, External Relations, Exploration, and Space Operations), in addition to other members of the NASA staff who have contributed significantly to this report.

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Executive Summary

Satellite servicing is an evolving technological activity currently in the early stages of development. NASA on-orbit experience, ranging from initial attempts to service early in the manned space program to present day planning, provides the data for future capability.

o The first EVA occurred during Gemini IV in June 1965; Apollo missions further extended EVA and IVA experience. Human participation in the execution of onboard experiments was an essential ingredient in the success of Skylab Missions. With the advent of the Space Transportation System, major advances in on-orbit servicing of spacecraft were demonstrated. Solar Maximum Mission and successful recovery of orbiting commercial satellites have established on-orbit satellite servicing.

o The Satellite servicing base today includes the existing Space Transportation System and the planned Space Station. Servicing support equipment, tools, and aids, in addition to servicing support systems currently in development, have evolved from prior experience. Future development of telerobotic and robotic servicing capabilities (e.g., Flight Telerobotic Servicer) will evolve to meet user needs.

o Space Station and scientific and commercial materials processing programs cannot exist without servicing as an enabling activity. Major science programs, including Hubble Space Telescope, Earth Observing Systems, and others, plan to achieve extended operational lifetimes and mission flexibility through the use of on-orbit servicing. The NASA Office of Space Science and Applications (OSSA) is planning to use on-orbit servicing to benefit its key programs, for example, the Great Observatories: Hubble Space Telescope; Gamma Ray Observatory; Advanced X-Ray Astrophysics Facility; and Space Infra-Red Telescope Facility; and the Explorer Program. The importance of planning for servicing in the early stages of program definition development is recognized as essential. Modularization and reliability factors are important to reduce life cycle cost of spacecraft.

o An initial DoD study (the Space Assembly, Maintenance and Servicing Study--SAMSS) has not yet identified near-term military satellite servicing requirements. NASA continues to work closely with the DoD in the area of satellite servicing through a Memorandum of Agreement.

o Availability of on-orbit satellite servicing may contribute to lower insurance coverage rates for commercial spacecraft. However, U.S. Government payloads are not impacted by insurance charges.

o NASA pricing policies established in 1985 are now under review as a result of changes to NASA operations.

o NASA proposes that utilizing satellite servicing enhances the maintenance and upgrading of national investments in space systems.

Satellite Servicing Terminology

For purposes of clarity in meaning, satellite servicing is defined as any activity performed on orbit to assemble, maintain, repair, resupply, upgrade, deploy, retrieve or return various spacecraft and/or facilities. To assist the reader with an understanding of these terms, each function is defined as follows:

(1) Assemble: join elements to form entities such as antennas, platforms, and spacecraft.

(2) Maintain: perform activities required for continuation of system performance at an acceptable level.

(3) Repair: return failed or degraded units to acceptable operation.

(4) Resupply: replenish consumables such as cryogens, propellants, other fluids, and raw materials.

(5) Upgrade: replace payload instruments or spacecraft bus subsystems with hardware of greater capability.

(6) Deploy: (a) release and provide initial separation distance, or (b) unfold/extend an appendage or long structure.

(7) Retrieve: rendezvous, capture, and stow.

(8) Return: transport from retrieval point back to a base such as Space Station or Earth's surface.

A number of commonly used acronyms and terms referred to throughout the document are also defined below:

EVA - extravehicular activity: Operations performed by crew members wearing space suits outside a habitable environment.

IVA - intravehicular activity: Operations performed by crew members within a habitable environment.

MMU - manned maneuvering unit: a multipurpose astronaut mobility unit allowing short-range free flights.

RMS - remote manipulator system: a 55 foot teleoperated arm on the STS for spacecraft deployment and proximity manipulation.

OMV - orbital maneuvering vehicle: A propulsion stage now in development that will be capable of transporting payloads between low Earth orbits and performing a number of different missions. The OMV is a reusable vehicle capable of being deployed from the Space Shuttle. Alternatively, the OMV may be based at the Space Station for deployment to retrieve accessible spacecraft and return them to the Space Station for refurbishment and reuse.

OTV - orbital transfer vehicle: A potential propulsion stage that will be capable of transporting payloads from low Earth orbits to higher energy orbits including the geostationary transfer ellipse and earth escape trajectories. The OTV is planned as a reusable vehicle capable of being deployed from the Space Shuttle and retrieved, or (alternatively) based at the Space Station for subsequent refurbishment and reuse.

Spacecraft/Satellite - The combination of mission equipment and carrier spacecraft capable of autonomous operation in space.

Introduction

On-orbit Satellite Servicing is a capability in an early stage of evolution. To date, such servicing has been entirely dependent on the presence and support of humans in space. Dependence on man has allowed great flexibility in the servicing tasks attempted since human beings are inherently inventive and dexterous. However, it has also severely limited the number of programs that have used or can use such a capability, since such programs must be associated with, or have the capability to achieve, a close proximity with the manned space vehicle.

Activities that are now acknowledged as essential elements of satellite servicing have been present in various forms since the early days of the Gemini program. The technologies of docking, assembly, remote manipulation, and Extravehicular Activity (EVA) which are an integral part of NASA's current servicing capability were first developed to support the operational needs of the manned space program. Early servicing activities, (for example, the replacement of the Skylab sun shield) were, in fact, undertaken as a necessary part of the program, rather than as a deliberate demonstration of on-orbit servicing. The many instances of on-orbit servicing performed on a more widely defined and less visible basis, however, also merit attention. Intravehicular activity (IVA), manned activity which takes place in orbit specifically to maintain, repair, and upgrade internal spacecraft equipment is an example of low visibility servicing (e.g., recalibration, diagnosis and fault isolation, assembly and checkout of new equipment).

On-orbit servicing activities already demonstrated have proven both the technological feasibility and potential of servicing for certain applications. For example, the Solar Maximum Mission (SMM) and Syncom IV-3 repair missions provided a technological and experience base for planning the long-term on-orbit maintenance of other NASA free-flying spacecraft, including Hubble Space Telescope. The success of on-orbit assembly of EASE/ ACCESS on STS flight 61-B demonstrates the enabling capability of satellite servicing for construction of Space Station. The Station must also be maintained on-orbit in order to function as a permanently manned base. Servicing has been, and will remain, a vital ingredient of NASA's microgravity life sciences and materials sciences research programs and will be required to support the commercial ventures which may evolve from these programs.

"Classification of Servicing Activities" (Fig. 1) summarizes this discussion of past and future servicing efforts. Up to the present time, on-orbit servicing activities have occurred primarily as a by-product of other ventures, or as (very successful) feasibility experiments. In the future, some servicing activities will be essential as program enabling for on-orbit spacecraft evolution.

On-orbit servicing, however, has not yet proven to be applicable to a wide range of programs for a number of reasons. Programmatic implications, scientific and technical ramifications, and cost impacts associated with such a course of action are extremely complex. Tradeoffs will be required in satellite and payload design, orbit selection, science or applications data return, operational complexity, ground support, flight support, space transportation and on-orbit manned support and facilities. Advanced space technology development in automation and robotics, aeroassisted return from geostationary orbit, autonomous rendezvous and docking, in-space assembly and construction, and cryogenic fluid management may significantly expand the range of missions that can benefit from on-orbit servicing.

NASA is currently engaged in several pioneering ventures to better determine the programmatic benefits and costs associated with satellite servicing from the user viewpoint. The first experiment of this nature was the SMM repair mission. Upon repair completion, six of seven instruments were operational and the planned spacecraft operational life of three years was tripled to nine years. The restored spacecraft has provided invaluable data on non-solar subjects, e.g., a gamma-ray emission from outside our solar system, supernova SN 1987a, and ozone concentrations in the atmosphere. Two other Astrophysics Division free flyers which will provide invaluable information on program benefits and user support costs

CLASSIFICATION OF SERVICING ACTIVITIES

ACTIVITY \ TIMEFRAME	PRIOR TO 1987	BEYOND 1987
Servicing as a by-product of the manned space program	GEMINI EVA APOLLO SKYLAB SPACELAB	
On-orbit servicing experiments to demonstrate feasibility	SMM REPAIR SYNCOM IV-3 WESTAR PALAPA	
Required on-orbit servicing		U.S. LIFE SCIENCES FACILITY U.S. MICROGRAVITY FACILITY SS ASSEMBLY/RESUPPLY MULTIDISCIPLINARY ATTACHED PAYLOADS LDEF RETRIEVAL GREAT OBSERVATORIES EXPLORER PLATFORM
Optional on-orbit servicing		FREE FLYERS PLATFORMS

Figure 1

associated with the long term maintenance of unique systems are the Hubble Space Telescope and the Gamma Ray Observatory. (A report on the maintenance and refurbishment program planned for the Hubble Space Telescope was provided to Congress by NASA in 1986). In addition, the U.S. life science and materials science research facilities, planned for flight on the Space Station, should provide additional insight into the optimum levels of reliability, modularity, and serviceability in a manned and man-tended operating environment.

For on-orbit servicing to be cost-effective, a wide variety of cost factors, including life-cycle cost, must be taken into consideration (see Chapter 4). In addition to the basic costs of space transportation and manned support for servicing activities, users must consider flight systems and the ground logistics costs. This may include spares, tools, support equipment, test equipment, documentation, and sustaining engineering costs. Such considerations place importance on controlling developmental costs of repeatedly used items and lead to increased consideration of standard spacecraft, systems or subsystems, and interfaces. NASA is working toward commonality at the system and subsystem level.

Because of the dependence on manned servicing support, only those payloads which fly in inclinations and at altitudes accessible from the STS or the Space Station can currently be serviced. Alternate, non-manned, servicing capabilities will be required for servicing missions to be initiated from Expendable Launch Vehicles (ELV's) and to be conducted remotely at spacecraft in polar or geosynchronous orbits, or other orbital inclinations. NASA is conducting enabling research for such remote servicing activities by developing and utilizing telerobotic servicers for the STS and Space Station. Assuring different methods and approaches for such remote servicing is part of the Earth Observing System (EOS) Phase B study activities.

Since on-orbit servicing depends on program specific factors such as program objectives and orbit accessibility, decisions to plan for on-orbit servicing are made on a program by program basis. For those programs which do utilize on-orbit servicing, however, a servicing infrastructure is needed in order to exploit potential benefits.

In conjunction with a desire to share its extensive expertise in the application and utilization of on-orbit servicing, NASA is supportive not only of the servicing needs of NASA users, but also those of the DoD, domestic commercial, and foreign users. The commercial Industrial Space Facility (ISF) and ESA's Eureca are examples of commercial and foreign spacecraft that are being designed to utilize NASA servicing capability. Although the initial phase of the joint study with the USAF (the Space Assembly, Maintenance and Servicing Study--SAMSS) has not identified near-term military satellite servicing requirements, NASA continues to work closely with the DoD in the area of satellite servicing. This joint effort takes place through a Memorandum of Agreement designed to address on-orbit maintenance and repair.*

In the remainder of this report, each of the seven elements identified in the Preface is discussed as follows. Chapter 1 describes the experience to date with on-orbit servicing, from Gemini to the present. Chapter 2 addresses the use of the STS, Space Station, and other vehicles to support satellite servicing by describing current capabilities, considerations, and development activities for on-orbit servicing support. Chapter 3 provides a discussion of the pertinence of satellite servicing to satellite and vehicle design, while Chapter 4 discusses the pertinence to space programs in general. Chapter 5 addresses the coordination of current activities among the various users of servicing capabilities, including civilian, defense, private, and foreign communities.

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*A Memorandum of Agreement (MOA) between NASA and the DoD for joint DoD/NASA on-orbit maintenance and repair was signed in June 1986. The purpose of this MOA is to establish the collaborative relationship between NASA and the DoD to institutionalize on-orbit maintenance as a design option for current and future space systems. Under this MOA, NASA and the DoD have participated in the SAMS Study. A report on the initial stage of this study was released in June, 1987. Since this is an on-going study with no conclusions determined at this time, it will not be discussed in detail within this report.

Chapters 6 and 7 discuss insurance and pricing issues, respectively. Chapter 8 presents NASA goals and objectives and their relationship with possible national goals and objectives.

As an established highly defined procedure, satellite servicing can enhance, protect, and maintain satellites on orbit. While the universal application of this technology to all classes of free flyers and Space Station payloads is questionable, there exists a range of applications (see Fig. 1) which are entirely dependent on such servicing for their existence and for which on-orbit servicing at some level is appropriate. Satellite servicing is a valuable adjunct to our technology base, ensuring our ability to enhance and protect our capital investment in space satellites and vehicles while preparing a capabilities path to achievement of NASA and national goals in space.

Chapter 1: Experience To Date

o Experience to date with on-orbit satellite servicing, including cost of such operations and the fees charged to non-NASA users.

This segment of the report addresses major milestones in the development of satellite servicing within NASA over the past two decades. Impacts to cost are discussed throughout the report. Pricing policy and fees charged to non-NASA users are addressed in Chapter 7.

As a matter of record, component capabilities which make up satellite servicing have been under development since the Gemini days of the manned space program. The dramatic quality of EVA activity that took place during the Gemini program captured public attention although the activity was not performed with satellite servicing in mind; rather, it was aimed at exploring the capabilities of man in space. This capability exploration continued into the Apollo program and developed into an integral part of the Skylab program where unplanned EVA servicing activities were necessary to rescue the mission. To date, Skylab, Spacelab, and Shuttle middeck experiments have required some degree of Intravehicular Activity (IVA) servicing. The opportunity to demonstrate man's in-space capabilities was greatly expanded within the Shuttle program. In particular, EVA mobility was increased, satellites were retrieved and repaired in low-Earth orbit, and man's value to on-site problem-solving became clearer.

A major historical milestone summary of servicing capability development is presented in Fig. 2 and Fig. 3. Pre-Shuttle experience is summarized in Fig. 2, while Fig. 3 summarizes Shuttle-based experience. In addition to the milestones and accomplishments, their associated missions, and the mission dates, these figures also identify the types of servicing elements and capabilities demonstrated on each of these missions.

The following paragraphs provide a detailed description of the on-orbit servicing experience to the present time. Addressed are pre-1987 servicing

MAJOR HISTORICAL MILESTONES IN SERVICING CAPABILITY DEVELOPMENT (PRE-SHUTTLE EXPERIENCE)

			SERVICING ELEMENTS & CAPABILITIES DEMONSTRATED						
MISSIONS	MILESTONES & ACCOMPLISHMENTS	MISSION DATES	EVA	IVA	RETRIEVING	REPAIRING	RESUPPLYING	UPGRADING	OTHER ELEMENTS & SUBELEMENTS*
GEMINI 4	•FIRST U.S. EVA	JUN 3-7, 1965	•						
GEMINI 6/7	•RENDEZVOUS & STATION KEEPING	DEC 15-16/4-18, 1965							•
GEMINI 8	•RENDEZVOUS & DOCKING	MAR 16-17, 1966							•
GEMINI 10	•EXPERIMENT HARDWARE RETRIEVED FROM DOCKED AGENA WITH EVA	JUL 18-21, 1966	•		•				•
GEMINI 12	•DOCKINGS & 3 EVA'S	NOV 11-15, 1966	•						•
APOLLO 7	•LIVE TV BROADCAST FROM SPACE	OCT 11-22, 1968							•
APOLLO 9	•CREW TRANSFER BETWEEN DOCKED SPACECRAFT	MAR 3-13, 1969	•	•					•
APOLLO 11	•EXTENSIVE EVA ACTIVITIES & SAMPLE RETURN	JUL 16-24, 1969	•	•					•
APOLLO 12	•RETURN OF ELEMENTS OF DEPLOYED SPACECRAFT (SURVEYOR 3)	NOV 14-24, 1969	•	•	•				•
APOLLO 13	•EXTENSIVE ON-BOARD PROBLEM SOLVING & RESOURCE MANAGEMENT	APR 11-17, 1970		•					•
APOLLO 15	•USE OF LUNAR ROVER & IMPROVED SPACE SUIT	JUL 26-AUG 7, 1971	•	•					•
APOLLO 17	•SATELLITE DEPLOYED IN LUNAR ORBIT	DEC 7-19, 1972	•	•					•
SKYLAB 2	•SUNSHIELD DEPLOYED & SOLAR ARRAY RELEASED DURING EVA •EXTENSIVE IVA	MAY 25-JUN 22, 1973	•	•		•			•
SKYLAB 3	•SUNSHIELD & RATE GYROS REPLACED WITH EVA • EXTENSIVE IVA	JUL 28-SEP 25, 1973	•	•		•			•
SKYLAB 4	•COOLANT SUPPLIES REPLENISHED •ANTENNA REPAIRED WITH EVA •SINGLE EVA DURATION RECORD	NOV 16, 1973 - FEB 8, 1974	•	•		•	•		•

* *Includes rendezvous, docking, elements of telerobotics, assembling, deploying, and returning*

Figure 2

MAJOR HISTORICAL MILESTONES IN SERVICING CAPABILITY DEVELOPMENT

(SHUTTLE-BASED EXPERIENCE)

			SERVICING ELEMENTS & CAPABILITIES DEMONSTRATED						
MISSIONS	MILESTONES & ACCOMPLISHMENTS	MISSION DATES	EVA	IVA	RETRIEVING	REPAIRING	RESUPPLYING	UPGRADING	OTHER ELEMENTS & SUBELEMENTS*
STS-7	•RMS DEPLOYMENT & RETRIEVAL OF SPAS-01 FREE FLYER	JUN 18-24, 1983			•				•
STS-9	•SPACELAB 1 WITH EXTENSIVE IVA	NOV 28-DEC 8, 1983		•					•
41-B	•MMU & FLUID PUMPING DEMONSTRATED • SMM REHEARSAL	FEB 3-11, 1984	•				•		•
41-C	•SMM RETRIEVED, REPAIRED & REDEPLOYED	APR 6-13, 1984	•		•	•			•
41-D/F	•31-M EXTENDED SOLAR ARRAY DEPLOYED & RETRIEVED •ICICLE REMOVED FROM SHUTTLE SURFACE WITH RMS	AUG 30-SEP 5, 1984							•
41-G	•ON-ORBIT FUEL TRANSFER & FUEL VALVE RETROFIT DEMONSTRATED	OCT 5-13, 1984	•				•	•	•
51-A	•PALAPA B2 & WESTAR VI RETRIEVED & RETURNED	NOV 8-16, 1984	•		•				•
51-B	•SPACELAB 3 WITH EXTENSIVE IVA	APR 29 - MAY 6, 1985		•		•			
51-F	•SPACELAB 2 RMS DEPLOYMENT & RETRIEVAL OF PDP	JUL 29 - AUG 5, 1985			•	•			•
51-I	•SYNCOM IV-3 RETRIEVED, REPAIRED AND REDEPLOYED	AUG 24-SEP 1, 1985	•		•	•			•
61-B	•EASE/ACCESS ASSEMBLY & DISASSEMBLY WAS FIRST SPACE STATION ASSEMBLY REHEARSAL	NOV 26-DEC 3, 1985	•						•

* *Includes rendezvous, docking, elements of telerobotics, assembling, deploying, and returning*

Figure 3

activities cited in Fig. 1 encompassing enabling technologies and actual on-orbit servicing experience.

ENABLING TECHNOLOGIES

Gemini Milestones

The Gemini program produced many significant milestones for the development of satellite servicing capabilities. The first American EVA was performed on Gemini 4 (June 3-7, 1965) by Astronaut Ed White. Gemini 6/7 demonstrated the feasibility of on-orbit rendezvous and station keeping and Gemini 8 demonstrated rendezvous and docking with a target vehicle. Capabilities continued to advance as Gemini 10 demonstrated the ability to retrieve experiment hardware from outside a spacecraft.

On Gemini 12, man-in-space capability was demonstrated outside the spacecraft during record-setting EVAs. Furthermore, the value of ground-based man-in-space simulation was demonstrated by this mission, when excellent correlation was observed between flight and simulation measurements of such EVA-related factors as astronaut heart rate, metabolic energy expenditure and manipulation of tools.

Apollo Milestones

Satellite servicing capability continued to evolve throughout the Apollo Missions. An essential component for future telerobotic servicing operations, live television, was first used in space by Apollo 7 (October 11-22, 1968). A major IVA capability was demonstrated on Apollo 9, when the first internal crew transfer between docked spacecraft (the Lunar Module and the Command Service Module) was successfully accomplished. The EVA experience base was dramatically extended on Apollo 11, when the first significant deployments occurred (a flag and numerous scientific instruments were placed on the lunar surface), and an extensive retrieval of samples performed. The first retrieval and return to Earth of elements from a previously deployed spacecraft (Surveyor 3) was performed by the crew of Apollo 12.

The value of man for extensive on-board problem solving, mission modification, and resource management became clear on Apollo 13 (April 11-17, 1970) when a fuel cell oxygen tank exploded, crippling the vehicle. On this mission, crew members extensively modified operation of their spacecraft systems and rationed limited on-board resources to survive their life-threatening emergency.

Significant mobility aids (the Lunar Roving Vehicle and an improved space suit) were successfully introduced on Apollo 15. On the final lunar mission (Apollo 17), the first satellite deployment from a manned spacecraft occurred when a scientific subsatellite was released into lunar orbit.

Skylab Milestones

Human participation in the execution of onboard experiments was an essential ingredient in the success of Skylab Missions. Although this occurred mainly in an IVA mode. the retrieval of data from some instruments required EVA. Man's ability to implement work-arounds for anomolous situations were fundamental to the success of this series of missions and proved conclusively that major elements of satellite servicing were technically feasible.

Crippling damage from the launch of the Skylab was repaired by means of EVA on the Skylab 2 (May 25-June 22, 1973) mission when a makeshift replacement sunshield was deployed, and the available electrical power was doubled by freeing a solar array which had failed to deploy. Skylab 3 crew replaced the laboratory's rate gyros and the makeshift sunshield with a more effective version. During the Skylab 4 mission (a final visit to Skylab), the astronauts demonstrated the first fluid replenishment (laboratory coolant), performed a repair of an external antenna, and set a new record of about seven hours for a single EVA.

Space Shuttle Achievements

The Space Shuttle has significantly expanded the potential for on-orbit service as a result of its unique capabilities, relatively frequent flight opportunities, and flexiblity. Satellite servicing capabilities, which were developed as an integral part of the manned program, have been applied directly to the on-orbit servicing of several unmanned satellites, with successful results. In addition, new capabilities, e.g., the use of the remote manipulator arm, have been developed, tested, and applied to on-orbit servicing tasks.

Servicing-related capabilities began development early in the Space Shuttle test flights with the first Remote Manipulator System (RMS) operations on STS-2 (Nov. 12-14, 1981). This capability was positively affirmed on STS-3 (March 22-30, 1982), when, for the first time, a payload (the Plasma Diagnostics Package) was removed and returned using the RMS. This package was lifted into space where measurement was achieved and then was swung back into its mount in the cargo bay. The crew of STS-7 provided a demonstration of proximity operations with the RMS deployment and retrieval of the SPAS-01 (Shuttle Pallet Satellite) free flyer. STS-9 carried out the first of four Spacelabs. All four Spacelab missions provided extensive IVA experience and demonstrated man's unique capability to maintain, repair, and if necessary, restructure experiments and equipment while on-orbit to obtain scientific benefits.

As a major milestone to the enhancement of EVA capabilities, STS Flight 41-B provided the first on-orbit demonstration of the Manned Maneuvering Unit (MMU), a device which greatly increases an astronaut's EVA range and mobility. Also on 41-B, fluid pumping was demonstrated and a contingency retrieval of an unintentionally deployed foot restraint occurred. The astronauts also practiced MMU docking for the upcoming Solar Maximum Mission (SMM) repair flight.

On STS 41-C, the Solar Maximum (SMM) Repair Mission (April 4-13, 1984), NASA planned and conducted its first formal experiment in on-orbit satellite servicing and repair. After an unsuccessful MMU (Manned Maneuvering Unit) docking attempt, the SMM spacecraft was grappled with the RMS, and maneuvered into the Shuttle's cargo bay. There the astronauts replaced the spacecraft's failed attitude control module and performed minor experiment repairs on the X-ray polychromator and the coronograph/

polarimeter science instruments with a single EVA. The Solar Max was then redeployed. The activity extended the operational life of the SMM and permitted significant gamma ray measurements to be made on the new supernova 1987a, as well as continuing SMM's long-term studies of solar activity. At this time, SMM continues to function as a scientifically productive spacecraft.

During the flight of STS 41-D/F, the RMS was deployed to remove a dangerous waste-water icicle from the Shuttle's exterior surface. An extended structure (a 31-meter solar array) was also deployed and retrieved. Mission 41-G demonstrated capability for on-orbit fuel transfer, and a fuel valve retrofit.

Probably the most highly visible satellite servicing events to date occurred on Mission 51-A; the retrieval and return to Earth of the Palapa B-2 (Indonesia) and Westar VI (Western Union) commercial communications satellites. Both satellites had been deployed from the Shuttle nine months earlier on Mission 41-B, but failures of their Payload Assist Modules (PAMs) resulted in their being placed in unusable low Earth orbits. The Palapa was retrieved first, followed by Westar. For both, the MMU was used for the initial capture; attachment hardware incompatibilities then forced the use of a manual contingency berthing procedure. Ultimately, both spacecraft were successfully returned to Earth, demonstrating NASA's capability to recover spacecraft from low Earth orbit.

An attempt was made on 51-D to repair the SYNCOM IV-3 satellite deployed on that flight by engaging a sequencer lever with a "fly-swatter" mounted to the RMS by means of EVA. (Analyses indicated that a switch lever on the satellite that activates the sequencer for the satellite may not have worked properly.) Although this particular attempt did not remedy the problem, the satellite was subsequently successfully retrieved and repaired during 51-I with an EVA. This mission clearly demonstrated that certain types of satellite repairs could be accomplished on-orbit.

Servicing experience with significance to Space Station assembly was demonstrated on Mission 61-B (November 26-December 3, 1985) during the

EASE/ACCESS structure operations. Two sample designs for Station truss structures were repeatedly erected, manipulated, and disassembled to gather timeline and engineering data. Installation of simulated utility lines was also performed, and the ability to repair components in an assembled truss structure was demonstrated.

o The use of the Shuttle, the Station, and other space vehicles to carry out or support satellite servicing.

OVERVIEW OF SERVICING-BASE CONSIDERATIONS

The existing STS and the planned Phase 1 Space Station are two manned facilities from which activities may be conducted to support on-orbit servicing. All servicing currently requires the direct support of humans in space and is Shuttle-based. Because of the propulsive energy required to change the orbital inclination of earth orbiting vehicles, and Shuttle operational capability, only free flying satellites in orbits with inclinations in ranges 28 degrees to 57 degrees and altitudes up to about 320 nautical miles can be serviced. This range can be extended up to 1400 nautical miles with plane changes of up to 7.5 degrees with the planned Orbital Maneuvering Vehicle (OMV).

Should the Vandenberg STS launch capability eventually be activated, high inclination (polar) satellite orbits could also be accessed from an STS base. Otherwise, high inclination satellites will have to rely on remote, robotic, or telerobotic, Expendable Launch Vehicle (ELV) based servicing capability that has yet to be developed. Such a capability is already being studied by NASA in its Earth Observing System (EOS) Phase B studies, and was assumed to be a primary servicing tool in the NASA/DoD SAMS study.

Orbital regions defined in the SAMS study are: low altitude/low inclination, low altitude/mid inclination, low altitude/polar orbit, high altitude/mid-inclination, and geosynchronous. The potential means of access to each of these five orbital regions is indicated in Fig. 4. Shaded areas in a row of this table represent regions which are inaccessible by the corresponding vehicle. Note that some vehicles exist, some are in the planning stages, and some are at a purely conceptual stage. A coarse timeline (see Fig. 5) illustrates how these vehicles may be used. This figure is intended to serve only as an example.

VEHICLE APPLICABILITY TO ORBITAL REGIONS

ORBITING REGION / VEHICLE	LOW ALTITUDE/ LOW INCLINATION	LOW ALTITUDE/ MID INCLINATION	LOW ALTITUDE/ POLAR ORBIT	HIGH ALTITUDE/ MID INCLINATION	GEO-SYNCHRONOUS
STS	●	●	ASSUMES VAFB LAUNCH		
SS	●				
OMV	FROM THE STS OR SS	FROM THE STS OR SS	FROM THE STS ONLY	FROM ELV	
OTV				FROM THE STS OR SS	FROM THE STS OR SS
ELV	●	●	●	●	●
COMMENTS	(1) SERVICING OF FREE FLYERS / PLATFORMS AT THE SS INVOLVES RETRIEVAL BY OMV / OTV (2) POLAR ORBITING SPACECRAFT CAN BE SERVICED FROM STS (VAFB LAUNCH) OR ELV's ONLY				

Figure 4

USE OF STS, SS AND OTHER VEHICLES FOR SERVICING*

	STS	*SS*	*OTHERS*
NEAR TERM CURRENT - 1994	• FREE-FLYER SERVICING	• N/A	• N/A
MID TERM 1994 - 2000	• FREE-FLYER SERVICING • SS ASSEMBLY • RESUPPLY OF SS	• SERVICING OF SS ATTACHED PAYLOADS • SERVICING OF FREE FLYERS & PLATFORMS	• USE OF OMV TO DEPLOY AND RETREIVE FREE FLYERS
LONG TERM > 2000	• FREE-FLYER SERVICING • RESUPPLY OF SS	• SERVICING OF SS ATTACHED PAYLOADS • SERVICING OF FREE FLYERS & PLATFORMS • ASSEMBLY OF LARGE PAYLOADS	• USE OF OMV/OTV TELEROBOTIC SERVICING • USE OF OTV TO TRANSFER TO AND FROM GEOSYNCHRONOUS • USE OF ELV'S

Figure 5

Note: Many of the mid and long term payloads are still in the planning and development stage and have not yet been approved for development

As a result of the previous on-orbit servicing activities discussed in Chapter 1, NASA has already developed an extensive array of ground support equipment, flight support equipment, and Shuttle-based servicing hardware and capabilities. Additional ground-based and space-based elements are currently being developed to support planned NASA on-orbit servicing activities, such as the maintenance and upgrade of the Hubble Space Telescope, and the on-orbit refueling of the Gamma Ray Observatory. A comprehensive servicing facility, including a protective enclosure, external storage facilities, work benches, and a dedicated remote manipulator system, has also been defined as part of the Space Station Phase B study activities. This facility will not be implemented as part of the Phase 1 Station but may be incrementally developed, as part of a continued Station evolution, as required to support user demands.

The following sections provide an overview of the existing and planned servicing capability including servicing support facilities, equipment, tools and aids developed by NASA for use in its continuing on-orbit servicing activities.

<u>Shuttle</u>

In the near term, i.e., until the mid to late 1990's, the Shuttle will be the only manned facility available to support on-orbit servicing. Although more limited than the Space Station, in terms of the servicing materials that can be aggregated on-orbit to support a specific servicing mission and the amount of EVA and IVA time available, the Shuttle has three advantages:

a) Flexibility of access to low to mid-altitude, mid-latitude, orbiting satellites;

b) Ability to rendezvous with a satellite; and

c) A crew.

OMV/OTV

A key capability expansion of Shuttle-based and Station-based servicing is the Orbital Maneuvering Vehicle (OMV) which can be used for satellite placement, retrieval, and reboost. The OMV is now in development with a planned initial capability of 1993. It is a reusable, remotely controlled, free-flying system capable of performing a wide range of on-orbit services in support of orbital payloads.

Multiple propulsion systems and on-board avionics will enable the OMV to deliver and retrieve satellites in orbits not otherwise achievable from the Shuttle. Precision maneuvering for proximity operations (including docking with an orbiting satellite) will be accomplished by man-in-the-loop control via an OMV control station. Eventually, both the OMV and the OTV might also be equipped with "smart front ends" (i.e., with robotic or telerobotic servicers) so that in-situ satellite servicing could also be conducted. When used with the Shuttle, the OMV will be carried into orbit as part of the servicing payload. For Station-based servicing, the OMV will be stored at the Station and will be used for multiple servicing events before being returned to earth. Thus, the OMV can be both a servicing tool and a servicing candidate in the Space Station era.

The OTV is planned as an advanced upper stage that will carry cargo, and perhaps humans, from low Earth orbit to geosynchronous orbit and beyond. The exact capabilities and configuration of the OTV will be defined in the early 1990's in parallel with NASA's new initiative definitions. In past studies of OTV concepts, several options have been the subject of trade-off studies. These include: the use of cryogenic or storable propellants; a reuseable or expendable design; ground-basing or space-basing; an all-propulsive vehicle or the use of an aerobrake for return flights; and delivery to low Earth orbit on the Shuttle or on a cargo vehicle. In most concepts, the OTV has the flexibility to evolve to meet increased mission requirements. For example, the initial OTV may be designed to deliver payloads to geosynchronous orbit, while a later version may be used to ferry humans between low Earth orbit and the Lunar surface. The initial OTV will most likely be a cryogenic vehicle with the capability to deliver at least 10,000 pounds of cargo to geosynchronous orbit or propel equivalent payloads to the Earth escape velocities required for advanced planetary exploration.

Space Station

The baseline Space Station (Phase 1) will have the capability to service and upgrade its own facilities as well as the internal and external attached payloads. There will also be a capability to provide, on a case-by-case basis, some servicing of free-flyers in the vicinity of the Station. Servicing elements will include the FTS, the Phase 1 Mobile Servicing Center (MSC) which includes the RMS, a mobile transporter, and standard equipment such as servicing tools and translation aids. These elements, in combination with the permanent presence of astronauts in an environment more controlled than that of the Space Shuttle, ensure a far more extensive EVA servicing capability than previously available.

Studies will be conducted to maintain the option of providing an effective early servicing capability for free-flyers and attached payloads. These studies will reveal more precisely how to take advantage of the capabilities afforded by the baseline Station. A first step is evaluating the capabilities needed to satisfy servicing, assembly and storage requirements. Additional efforts will analyze possible EVA servicing aids that might include a case-by-case application of sun-impingement protection, thermal control, and contamination traps, shields, and tents. The IVA servicing capability, including the workbench area, is available to support EVA.

Program plans include servicing the ESA-provided Man-Tended Free-Flyer (MTFF) at the Space Station after the completion of assembly and operational verification. Additional free-flyers that may be serviced from the Space Station include commercial platforms, the Hubble Space Telescope and the Gamma Ray Observatory, AXAF, SIRTF, as well as other OSSA assets that require servicing. As the Station evolves, one possibility is to add a more extensive servicing capability as the initial increment of Space Station evolution. These capabilities could include an enclosed full-sized servicing facility and Orbital Maneuvering Vehicle (OMV), enhancements to the MSC, and an additional RMS.

ELV

The use of Expendable Launch Vehicles (ELVs) for on-orbit servicing of satellites is still in a preliminary stage of study, and requires the development of expanded vehicle capabilities, such as automated docking and servicing capabilities. ELV-based servicing has the potential advantage of access to spacecraft at all orbital inclinations and altitudes and the disadvantage that the servicing payload cannot be returned to earth after the servicing event. Possible solutions to this dilemma, currently under study by NASA and the DoD, include off-loading the robotic servicing devices from the ELV onto the spacecraft or platform and using them to support "self servicing" throughout the operational life of the spacecraft. No NASA mission has yet baselined the use of such on-orbit servicing, although the EOS mission is still considering this approach in its tradeoff studies, together with the use of non-serviceable (expendable) spacecraft.

Spacecraft Rendezvous and Retrieval

Retrieval of spacecraft for servicing requires that the orbital planes of the spacecraft and the servicing vehicle are in alignment. The opportunities for co-alignment range from a daily launch window for a KSC launched, dedicated STS servicing mission, to opportunities permitted by alignment of a spacecraft to be serviced by Space Station. These servicing opportunities may range from days to periods greater than one year. This happens due to the differential precession of the orbits. STS-shared retrieval missions may have constrained launch windows, and therefore may have fewer than daily launch opportunities because of manned spaceflight constraints such as lighting conditions, the launch-window constraints of other payloads, or other factors.

For Space Station based servicing of the Hubble Space Telescope, which does not have its own propulsion capabilities, the Hubble Space Telescope orbit plane and the Space Station orbit plane will align approximately every 14 months and will remain aligned sufficiently to allow retrieval for several days. This interval is the "plane window." Frequency of orbit plane alignment depends on the respective altitudes of the two orbits. Actual accessibility for rendezvous and retrieval, the "phase window," will vary and is dependent on the operational capabilities of the Space Station, the OMV, and the spacecraft to be serviced.

Careful planning to assure successful rendezvous and retrieval of spacecraft for service is required. Given the above considerations of orbital mechanics, servicing missions launched from KSC may be appropriate where more frequent orbital alignments are required, while the Space Station may be utilized for preplanned repair and maintenance of spacecraft.

EXISTING SERVICING HARDWARE AND CAPABILITIES

This segment of the report discusses hardware and capabilities that are existing, under development, and planned. In order to undertake the various on-orbit servicing activities that have been required to support NASA's manned space program, an extensive array of ground-based and space-based support equipment, crew aides, tools, and procedures has been developed. This array of servicing hardware and capabilities has been further refined and extended to support NASA's planned Shuttle-based on-orbit servicing experiments. As a result, there currently exists versatile equipment and an associated experience base on which new users of NASA's on-orbit servicing capability can draw. NASA now has a catalogue of existing servicing tools which is in the process of being updated and plans soon to publish the new version.

The development of standard on-orbit servicing equipment and procedures is potentially of great value to NASA and non-NASA programs planning to make use of this new capability. First, the use of such equipment reduces the mission-unique development costs associated with on-orbit servicing. The use of standardized tools and procedures also reduces the servicing crew's ground-based training time, and lessens the risk of expensive mistakes on-orbit. In addition, since NASA has expended significant effort in making its equipment as efficient and reliable as possible, subsequent users can realize the benefits of this design optimization process. An example of such an optimized servicing tool is the Programmable Power Ratchet Tool, which may be regarded as the power driver analog of a conventional ratchet handle with unique control features. The concept originated at Marshall Space Flight Center in the course of man-in-space evaluations for Hubble Space Telescope (HST) servicing options. In searching for ways to speed up tedious manual operations, the advantages of a pneumatically powered ratchet driver were dramatically apparent. More significantly, such a tool may well make the difference in the completion of a mission. These types of tools and activities are expected to become standard through common use. Man-in-space activity that occurs while wearing a pressure suit is fatiguing and restricting; use of power tools offers reduction of these negative operational factors and improves and prolongs the productivity of the crewmember.

Existing Shuttle-Based Servicing Hardware and Capabilities

Flight-qualified Shuttle-based servicing hardware and capabilities (most of which have already contributed to successful servicing missions) are listed in Fig. 6 on the following page. The functional applicability of each servicing tool is described below:

EVA:

o Module Service Tool--powered device which drives the connection interface for equipment modules such as used on the Solar Maximum spacecraft.

o Smart Programmable Power Ratchet Tool--a recent development aimed at reducing the physical and mental workload in hardware interface operations.

o Monopropellant fluid coupling--developed as a working EVA operable model to stimulate incorporation of such interfaces in near-term spacecraft.

o Electrical connectors--self-aligning electrical connectors with internal circuit components are protected from damage during the engagement sequence.

EXISTING SHUTTLE-BASED SATELLITE SERVICING HARDWARE AND CAPABILITIES

	RETRIEVING RESUPPLYING	REPAIRING	UPGRADING	DEPLOYING	ASSEMBLING CONSTRUCTING
FLIGHT QUALIFIED HARDWARE •EVA MODULE SERVICE TOOL	•	•	•	•	•
SMART POWER RATCHET TOOL	•	•	•	•	•
EVA FLUID COUPLINGS (MONOPROP.)	•				
ELECTRICAL CONNECTORS	•	•	•	•	•
FLIGHT SUPPORT SYSTEM (FSS)	•	•	•	•	•
HAND TOOLS	•	•	•	•	•
MMU	•		•		•
•RMS	•	•	•	•	•

Figure 6

- o Flight Support System (FSS)--used for holding spacecraft of various designs in the Shuttle bay so that they can be serviced.

- o Miscellaneous hand tools--EVA-adapted versions of common tools (ratchets, vise grips, etc.).

- o MMU--multipurpose astronaut mobility unit allowing short-range free flights.

RMS:

- o RMS--a 55-foot teleoperated arm baselined STS mechanism for spacecraft deployment and proximity manipulation.

Associated Ground-Support Equipment and Facilities

Significant ground-based support equipment and facilities, which are an essential part of satellite servicing activities, exist at the various NASA space flight centers. These resources include neutral-buoyancy tanks, Shuttle and Space Station models and simulators, large air-bearing floors, dynamic docking simulators, robotic simulators, and Shuttle payload integration facilities. These facilities are essential because they provide realistic crew training in servicing activities, and verification of servicing hardware and procedures. They also facilitate mission planning and support all aspects of hardware design and development. These facilities will be made available to potential non-NASA servicing users on a cost-reimbursable basis.

SERVICING DEVELOPMENT ACTIVITIES

In addition to the array of existing hardware and facilities identified above, there are a number of potentially powerful servicing support systems currently in development. The systems will apply generally and support specific programs, like the Hubble Space Telescope, the Gamma Ray Observatory, AXAF, SIRTF, and EOS.

This section presents summary schedules for servicing hardware development and flight experiments (Fig. 7).

SATELLITE SERVICING HARDWARE DEVELOPMENT STATUS

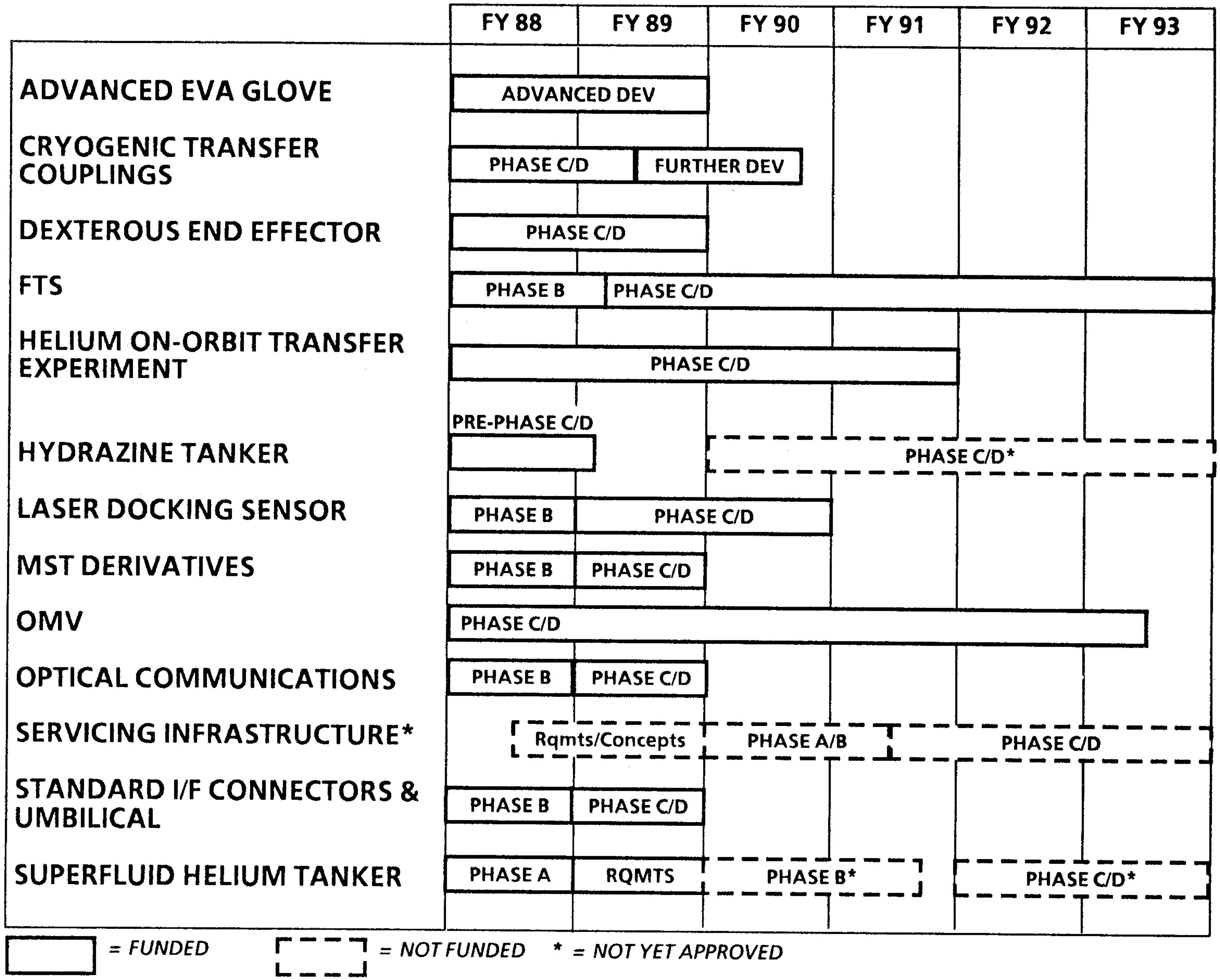

Figure 7

Following are descriptions of each major hardware item and experiment currently being developed:

- Advanced EVA Glove--a funded project designed to increase dexterity, tactile sensing and mobility, and to decrease effort in hand work during EVA.

- Cryogenic Transfer Couplings--a funded project being developed as an EVA model for incorporation in near-term spacecraft.

- Dexterous End Effector--a funded project combining force/torque sensor with a mechanical hand for the RMS to allow more refined RMS operations than currently achievable.

- Flight Telerobotic Servicer (FTS)--a robotic system designed to assist in Space Station assembly and maintenance, and to be structured for evolutionary capabilities.

- Helium On-orbit Transfer Experiment (SHOOT)--a funded project for development of a Shuttle-based, in-bay demonstration of superfluid helium transfer under operational conditions will be performed.

- Hydrazine Tanker--being designed for spacecraft refueling. Prephase C/D has been funded; Phase C/D is not yet approved nor funded.

- Laser Docking Sensor--a funded project for the development of hardware designed to track a passive orbital target spacecraft with sufficient accuracy to enable soft docking with minimal thrusting near the target vehicle.

- Module Service Tool (MST) Derivatives--a funded project for development of end effectors modified to be mounted on the end of the RMS to facilitate non-EVA servicing operations from the STS; Lightweight MST--modified to reduce weight and facilitate ease of operation, and to operate as a front-end tool on the Flight Telerobotic Servicer (FTS), OMV and other teleoperated or remote servicing facilities.

o Orbital Maneuvering Vehicle (OMV) --a funded project to develop a reusable propulsion stage capable of transporting spacecraft and other payloads between low Earth orbit trajectories.

o Optical Communications--a funded project to provide local high bandwidth point-to-point communication capability for operations from the STS aft flight deck to local servicing sites.

o Servicing Infrastructure--coordinated hardware and technology development to support a well-defined user requirement database. Project is not yet approved for funding.

o Standard I/F Connectors and Umbilical--a funded project for development of a remote mateable/ demateable flexible umbilical connector to provide a remotely operated umbilical connector capability for electrical, gas, and fluid services; and the Umbilical Carrier Mechanism (with the passive half of the umbilical and carrier on a satellite to be serviced and the active half on the Shuttle) controls the connection of umbilicals to minimize disturbances to the satellite and Shuttle.

o Superfluid Helium Tanker--designed to resupply cryogenic coolants on board the SIRTF and possibly, the second-generation Hubble Space Telescope and AXAF instruments. Phase B and Phase C/D are not yet approved nor funded.

SERVICING EVOLUTION CONSIDERATIONS

As noted earlier in this report, on-orbit servicing is a capability which is still in an early stage of evolution. From the servicer side, it depends on the successful evolution of the current Shuttle-based capability and facilities of the Space Station. Once servicing support and facilities are available at the Station, further development of telerobotic and robotic servicing capabilities will take place. Such capabilities will benefit all servicing users, since they will decrease dependence on EVA. They will also benefit potential servicing candidates operating in orbits inaccessible to the Shuttle and Space Station.

With the advent of the OMV, many forms of spacecraft services will become possible. The OMV or the OTV may be used to return spacecraft to the STS or the Space Station for maintenance and/or resupply. In addition, direct spacecraft servicing may be performed by adapting special purpose mission kits to the OMV or the OTV which are capable of performing remote or in-situ maintenance of spacecraft, thus eliminating the need to return payloads. Fuel efficiency of telerobotic or robotic OTV servicing missions to spacecraft in geostationary orbits could be further enhanced by the use of aerobraking to assist in the return from geostationary orbit.

The remote services may take two generalized forms; remote module exchange of failed spacecraft elements or replenishment of onboard expendables. Perhaps both may be desirable on the same mission. These functions, in effect, extend man's ability to perform maintenance and other mission support operations remote from the STS through the adaptation of specialized "effectors" or servicing and refueling kits.

In addition to the previously mentioned functions, it has long been recognized that a need exists to be able to capture unstable and/or inactive spacecraft and certain classes of debris. Ongoing studies are being directed toward the definition and development of systems to expand the OMV capability for capture. This interest addresses the economic value of some classes of spacecraft which have failed prior to the end of their useful life and threaten collision with other orbiting systems. Such spacecraft could be recovered and reflown as was demonstrated in the retrieval, repair and redeployment of the Solar Maximum Mission spacecraft.

Where costs of on-orbit servicing are associated with NASA's servicing support, the agency will continue its efforts to develop more efficient and reliable support equipment and facilities. NASA will also provide potential users with guidance on how best to make use of on-orbit servicing. This advice will be drawn from the NASA user's own experience in using on-orbit servicing to assemble structures, to maintain or repair systems, to resupply consumables, to upgrade payloads, and to retrieve, deploy or return spacecraft and payloads.

Since the integrated logistics support required for few-of-a kind missions will continue to be a significant cost driver, NASA will continue to develop and promote the use of common systems and subsystems, as well as common interfaces, support equipment, and tools. This will reduce the cost of on-orbit servicing.

NASA is performing studies to determine the feasibility of employing ELV-based robotic servicing in polar orbits. The two concepts under study utilize a service carrier which is launched on an ELV. After rendezvous and docking, one scenario features a resident robot that exchanges ORUs and payloads which use Standard Interface Connectors (SIC). The service carrier is discarded. In the second scenario, the service carrier remains attached and functions as an extension of the original platform. NASA is considering generating guidelines to payload designers so that they may incorporate generic design features to facilitate possible future robotic servicing.

Finally, NASA will continue to look at the requirements and benefits of on-orbit servicing capabilities on a program by program basis, and will balance the life-cycle costs of such an approach with the scientific, commercial, or programmatic needs and benefits.

o Pertinence of satellite servicing to satellite and vehicle design.

Two kinds of programs currently plan to use on-orbit servicing. The first, which includes the Space Station and life science and materials processing programs, requires on-orbit servicing as an enabling activity; they cannot exist without it. The second, which includes the Great Observatories (Hubble Space Telescope, GRO, AXAF, and SIRTF), the planned reuseable Explorers, and the Earth Observing System (EOS) platforms, will use on-orbit servicing as an enhancing capability to achieve extended operational lifetimes and/or mission flexibility. These missions could, in theory, achieve their program goals by other means, but choose to use the servicing infrastructure to benefit their missions.

For both kinds of programs, planning for on-orbit servicing has to begin at a very early stage in the program definition process; i.e., in the feasibility and conceptual study activities. Some of the most fundamental decisions that must be made concern the tradeoffs between scientific (or program) goals and objectives and the need for manned or unmanned on-orbit servicing. Thus, a solar physics or astrophysics mission may have to balance the scientific benefits of the continuous observations possible at geosynchronous orbit against the extended operational lifetime and scientific payload upgrade potential of a more accessible spacecraft.

ON-ORBIT SERVICING CONSIDERATIONS

Once on-orbit servicing has been established as desirable for a program, then studies must be undertaken to determine such factors as: systems architecture; level of modularity of spacecraft and payload; degree of reliability; frequency of servicing needed during lifetime of spacecraft; and level of commonality of systems or subsystems internal and external to the Mission. Inherent in the design decisions associated with serviceability are those which make the planned on-orbit servicing activities safe and efficient for human servicers and feasible for the less dexterous robots. For example, a means must be provided to make the spacecraft safely approachable. If the spacecraft is to be transported to another location before servicing commences, its structure must be capable of surviving the loads (i.e., shock, acceleration, vibration, etc.) imposed by the transporter. The spacecraft also must be protected from contamination sources during all phases of the servicing process, and the thermal environment maintained in a safe range throughout the operation.

Another important consideration in the design process is the allocation of interface responsibilities. For example, in the case of satellite capture and retrieval, the first concern in approaching a satellite is to eliminate both straight-line motion and rotation. For broadest applicability, this responsibility should be given to the servicer, since some spacecraft may be rendered inactive by the failure which prompted the servicing mission. The next concern is whether the spacecraft geometry allows a servicer to get close enough for docking; a rearrangement of appendage placement may be necessary. Obviously, servicer attach points must be made available at the docking area, and EVA handholds must be provided for manned servicing targets. Protective covers must be installed for fragile satellite structures, and satellite hazards to the servicer or astronaut must be eliminated.

If the servicing operation is not to take place in-situ but rather at a distant base, the satellite must be able to survive the transportation environment. Provision must be made for appendage stowage and subsequent redeployment if launch loads exceed survivable limits. If the satellite's thermal conditioning and power systems are adversely impacted during the transportation phase, the servicer must be capable of supplying the appropriate supplements to the satellite if required.

Spacecraft Modularity

If design solutions to all of these concerns can be found, the question of robotic versus human servicers and human servicer skill level must then be addressed. It is generally accepted that the easiest and most efficient on-orbit servicing requires modularization of a spacecraft into a number of easily exchanged Orbital Replacement Units (ORUs). The fewer the ORUs, the easier the on-orbit servicing event. However, ease of on-orbit servicing must be balanced against the potential cost of replacing an ORU containing both failed and functional systems. Transportation to and from space to support the servicing event must also be taken into consideration. Ideally, today's satellite ORUs should be designed for manipulation in both EVA and remote servicer modes; this includes considerations for grappling points, mass, and geometry. The ORUs should be designed for easy insertion and removal in both modes. The considerations here are for alignment aids, interface verification, and connection designs for power, thermal, fluid, and communication services between the ORU and satellite core.

Spacecraft Environmental Considerations

Another ORU design concern is that of survivability during the space transportation, on orbit storage, and exchange processes; for example, some satellites will have varying degrees of sensitivity to contaminants emanating from the Shuttle and from the servicer. They will also be sensitive to the thermal environment (ORUs will also be sensitive to this environment). Although the ORU carrier will afford some level of contamination control and thermal protection and the servicer system will be designed to be as clean as possible, this concern still needs to be addressed by all satellites. Solutions to these concerns may involve servicer-installed covers for sensitive satellite components or servicer-provided thermal screens or enclosures.

DESIGN CONSIDERATIONS FOR ON-ORBIT SERVICING

The modular design of spacecraft required to facilitate on-orbit servicing has both positive and negative impacts. On the positive side, modularity and accessibility can make satellite integration and test more efficient.* A study for NASA by Martin Marietta estimated a 4% incremental cost increase for design and development and an estimated 8% per unit recurring cost

*"The NASA/GSFC MMS Experience", Edward Falkenhayn, December 1987.

increase for hardware.* A serviceable design may also result in a heavier spacecraft, with a 5 to 10% weight increase being estimated by many builders.

Other factors which must be considered by the users of payloads on serviceable spacecraft include: reduced surface space due to the presence of grapple fixtures and handholds; increased opportunity for damage during the servicing event; and probable down-time for spacecraft systems and payloads during servicing. Some positive considerations are the opportunities for expendables replenishment and instrument upgrades, repairs, or replacements.

Reliability

A vital question that must be addressed by the spacecraft designers is that of system reliability and the frequency of the servicing event. Clearly, there is great benefit to be gained from making spacecraft systems as reliable as possible to reduce servicing costs. Even when servicing is planned to effect the exchange or upgrade of a payload, or to replenish consumables, it is still desirable to reduce other servicing activities and the associated costs of servicing support. Ultimately, a limit is reached in which the cost of obtaining, screening and selecting high reliability parts and the associated weight penalties makes further reliability expensive compared with the cost of on-orbit servicing. The user must recognize this point and establish his reliability requirements prior to the start of the design phase.

Integrated Logistics Support Requirements

In designing a spacecraft for on-orbit servicing, and making the tradeoffs implied above, the more mundane requirements of ground-based and space-based logistics must not be forgotten. These requirements include: spares, tools, repair and refurbishment facilities, ground support equipment, ground

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*Report MCR-86-1339, Martin Marietta, Contract NAS 835625 with MSFC.

test equipment, shipping and handling equipment, documentation, sustaining engineering, crew training, flight support equipment, ground transportation, space transportation, and special crew aids and tools. While space transportation and the design for on-orbit servicing are both significant cost drivers in a user's budget for on-orbit servicing, the integrated cost of the remaining items can also be significant unless care is taken at the beginning of the program to minimize these costs.

The most effective way of reducing these residual costs is by use of standardized systems and subsystems. This allows several programs to share the cost of most of the ground-based and space-based support elements listed previously. The use by the Solar Maximum Mission of the Multimission Modular Spacecraft (MMS) assured the availability of spare spacecraft modules (ORUs) even though no provisions had been made for such a repair attempt within the program. The planned use of the Explorer Platform will exploit this capability for future Astrophysics Explorer Missions. Recognizing the significant benefits of commonality at both the system and subsystem level, the Space Station program has dictated that commonality be maximized throughout the Station and its Platforms.

o Pertinence of satellite servicing to NASA and other space programs, including science and applications programs.

The Solar Maximum Mission Repair was a highly visible and successful demonstration of NASA's ability to rapidly (i.e., within one year) mount and implement an unplanned repair mission on a modular spacecraft. The repaired SMM spacecraft has continued to collect valuable observations of solar activity during the ascending phase of this solar cycle and has obtained dramatic new gamma ray measurements on the supernova 1987a.

A major advantage of on-orbit servicing is that it has made possible the concept of the Great Observatories Program. By extending the on-orbit lifetime of four major astrophysics observatories: the Hubble Space Telescope (HST), the Gamma Ray Observatory (GRO), the Advanced X-Ray Astrophysics Facility (AXAF), and the Space Infra-Red Telescope Facility (SIRTF), it should be possible to achieve periods of overlap (or near overlap) between different sets of the Great Observatories, such that contemporaneous measurements can be made. The capability to make contemporaneous multispectral observations of selected features and phenomena in the universe will enable the world's astronomers to rapidly make significant advances in all fields of astrophysics.

The Great Observatories Program development is already underway. Both GRO and HST have already been approved and are in advanced stages of development. AXAF is a candidate for an FY 1989 new start, and SIRTF is in an advanced design stage, aiming at a new start in the early 1990s.

The first (visible and ultraviolet) element of the Great Observatories Program, the Hubble Space Telescope, was the first NASA payload specifically designed to make use of on-orbit servicing. The initial rationale for on-orbit servicing of HST was to assure long-term scientific excellence for the mission, through progressive introduction of ever-more capable scientific instruments at the focal plane of the 2.4-meter aperture telescope. The HST will function in space in exactly the same way that a major ground-based observatory functions on the ground, with provision made both for general observers and for a limited number of new instrument builders.

The second (gamma ray) element of the Great Observatories Program, the Gamma Ray Observatory, was not initially designed for on-orbit servicing. However, GRO's use of the MMS renders the spacecraft serviceable on-orbit. NASA now plans to replace MMS modules and replenish the GRO propellants as required to achieve an extended mission life. The nature of GRO's massive, complex, and intricately designed science instruments makes them impossible to replace on-orbit. However, most of the GRO instruments have inherently long design lifetimes and extensive scientific potential, and are hence compatible with the Great Observatories concept.

Although the remaining two elements of the Great Observatories Program have not yet received approval to enter the development phase, both are being designed to make use of on-orbit spacecraft servicing to achieve extended mission lifetimes. The third (x-ray) element of the program, AXAF, is a large aperture (1 meter) grazing incidence multi-element telescope with a cluster of scientist-developed instruments in its focal plane. Like the HST, AXAF will assure long-term scientific excellence through replacement of selected elements of the payload at later phases of the program. AXAF is also likely to make use of modular spacecraft systems which are common to those of the GRO or the HST. Thus the AXAF servicing program will also enjoy some of the benefits of system commonality.

The fourth (infra-red) element of the Program, the Space Infra-Red Telescope Facility (SIRTF), is also a large aperture telescope with a cluster of scientist-developed instruments at its focal plane. However, in order to make measurements in this wavelength range, both the telescope and the instruments must be cryogenically cooled. The availability of on-orbit servicing will enable SIRTF's cryogens to be replaced when necessary, as well as allowing failed or degraded spacecraft systems to be replaced. However, because of the design of the cooling system, scientific instrument replacement may not be possible. The SIRTF may achieve system commonality through use of HST or GRO-type spacecraft modules or may be the first Space Station co-orbiting platform.

Other Divisions within OSSA have similar plans. In particular, the Earth Sciences and Applications Program plans to make use of the Space Station's polar orbiting platforms as part of its Earth Observing System (EOS) program. EOS is currently in the planning phase, aiming for a new start in the early 1990s. On-orbit servicing from a Vandenberg-launched Shuttle or from an ELV would provide extended operational lifetimes and operational flexibility, and are options being evaluated. Additionally, both the Space Physics Division and the Solar System Exploration Division plan to use on-orbit servicing to assemble and maintain a number of Space-Station-associated attached payloads and near-orbiting spacecraft.

Of particular importance in the Space Station era are OSSA's plans for microgravity life sciences and materials sciences research. Facilities are being designed by NASA and the private sector to support both branches of microgravity research. The plans for NASA facilities are also being coordinated with those of the Station's international partners, the European Space Agency (ESA), Japan, and Canada, since all three plan similar facilities. On-orbit servicing in the form of resupply of consumables, harvesting of samples, and repair of failed systems is an inherent, enabling activity for both of these programs. Without such on-orbit support, research cannot be undertaken which will lead to commercial exploitation of the microgravity manufacturing environment, and commercial man-tended space processing ventures. It should be noted that these ventures will have to make use of both on-orbit servicing of the commercial (materials processing) payloads, and of the parent spacecraft or platforms. Thus, commercial users will benefit from NASA's on-orbit servicing of free flyers as well as support of the materials processing activities.

A summary of NASA's satellite servicing requirements is provided in Fig. 8a and Fig. 8b. These requirements exhibit varying degrees of firmness in terms of eventual implementation, the firmest of which are those derived from the published NASA FY88 budget, including out-years. Longer range

OSSA CANDIDATE MISSIONS FOR SHUTTLE-BASED SERVICING

MISSION	STATUS OF SPACECRAFT/ LAUNCH/ SERVICING	POTENTIAL SERVICING REQUIREMENTS				PROJECTED TIME FRAME
		RETRIEVING	REPAIRING	RESUPPLY-ING	UPGRADING	
SPACELAB MISSIONS	ANNUALLY BEGIN'G IN 89 PLANNED	●	●	●		89 - 96
SOLAR MAX RETRIEVAL	ON ORBIT	●				90
HUBBLE SPACE TELESCOPE	IN ASSEMBLY 6/89 PLANNED	●	●		●	92
EXPLORER PLATFORM	IN ASSEMBLY 8/91	●	●		●	MID 90's
GAMMA RAY OBSERVATORY	IN ASSEMBLY 1/90 PLANNED	●	●	●		94
ADV X-RAY ASTROPHYSICS FACILITY	95 PLANNED	●	●	●	●	98
SPACE IR TELESCOPE FACILITY	96 PLANNED	●	●	●	●	98
EARTH OBSERVING SYSTEM (EOS)	95 PLANNED	●	●	●	●	98

OTHER SHUTTLE - AND STATION-BASED SERVICING MISSIONS

MISSION	STATUS OF SPACECRAFT/ LAUNCH/ SERVICING	SERVICING REQUIREMENTS				PROJECTED TIME FRAME
		RETRIEVING	REPAIRING	RESUPPLY-ING	UPGRADING	
LDEF RETRIEVAL	ON ORBIT - PLANNED	●				89
EURECA (ESA)* (3 FLIGHTS)	PLANNED	●				91-92-->
INDUSTRIAL SPACE FACILITY (ISF)* (3 FLIGHTS PER YEAR)	PLANNED	●		●		92-->
SPACE FLYER UNIT (SFU)* - JAPAN	PLANNED	●				93
SPACE STATION	PLANNED	●	●	●	●	94-->
MAN TENDED FREE FLYER* (ESA)		●	●	●	●	97-->
LONG RANGE MISSIONS -LUNAR AND MARS INITIATIVES -MISSION TO PLANET EARTH -ROBOTIC EXPLORATION OF THE SOLAR SYSTEM	Under Consideration	← TBD →				LATE-90's -->

*REIMBURSABLE

Figure 8b

requirements are derived from the NASA Civil Needs Data Base (CNDB) which includes potential commercial and foreign missions; (Version 2.1, July 1987), the NASA mixed fleet manifest, and possible long-range missions being studied. The CNDB (currently being revised) is a data base used for transportation studies.

The Space Station era of satellite servicing begins with the on-orbit assembly of the Station, a major servicing achievement. Components of the Space Station will be carried to orbit by the STS beginning in 1994. The actual construction and operational verification of the Space Station requires the same servicing support elements that provide servicing capabilities for users. Specifically, assembly requires the ability to transport, manipulate, and mate numerous elements. Many of these same techniques will be used to repair, replace, and resupply early attached payloads. Studies will evaluate early attached payload requirements against the servicing capabilities as they are built-up over the Phase I period. Some of these attached payloads are referenced in Appendix A (OSSA Payload Summary charts).

The Space Station servicing functions required of the astronaut crew necessitates a combination of EVA and IVA that is enhanced by advanced robotics. Program planning anticipates 24 EVA man-hours from Shuttle-based Flights 1 through 10. There will be greater flexibility in EVA activities as these become Station-based after reaching Permanently Manned Capability (PMC).

The design for the core Station, platforms, payloads, and ground systems will consider baselining robotic assembly, maintenance, and servicing. To emphasize this directive, the Flight Telerobotic Servicer (FTS) is part of the first element launch to aid in the assembly of the Station. The FTS handles specific tasks for assembly, maintenance, inspection, and ORU change-out, and will be operable using both direct manipulator control and command sequences. Its design allows transport to different work sites as the Space Station develops. Additionally, Program plans stipulate employing the FTS for initial operations requiring telerobotic dexterous manipulation of attached payloads.

Assuming availability of a Vandenburg Shuttle launch, the baseline scenario for servicing the Polar Orbiting Platform (POP) consists of servicing at the Shuttle using the Remote Manipulator System (RMS), teleoperated end effectors, and EVA backup. This requires the POP to use its propulsion module to descend to Shuttle altitude. An alternate scenario requires servicing at mission altitude using the Shuttle, OMV, and the FTS.

Another piece of robotic servicing hardware on the manned station base is the Mobile Servicing Center. The MSC is an integrated system to support construction and assembly functions and features the U.S. provided mobile transporter and the Canadian-supplied interior and exterior control stations, an RMS, a special purpose dexterous manipulator (SPDM) for servicing tasks, and an MSC maintenance depot that holds tools and attachments. The MSC capabilities are added as the hardware arrives during the assembly sequence. Early functions include the capabilities to perform assembly tasks, maintenance and servicing, EVA support, orbiter docking, and the transport and servicing of attached payloads on external structures. Plans are to improve the MSC mobility on the truss structure around the Station. Two years after first element launch, the SPDM will provide end effector capabilities complementary to the FTS. The final addition of the maintenance depot provides the storage capability for the tools and attachments necessary to service the MSC.

When the Station achieves a permanently manned capability, servicing will become based at the Station with resupply for the Station and its payloads continuing as an STS service. In the steady state operational mode, (after completion of the baseline Station) all servicing and logistics needs will be accommodated within the planned five Shuttle-equivalent flights/year envelope.

Chapter 5: User Plans (Coordination of Current Activities)

o All potential users of satellite servicing capabilities including civilian, defense, private, and foreign satellites and space vehicles:

Since on-orbit servicing is currently heavily dependent on human intervention, only two national space programs, those of the U.S. and the U.S.S.R. can undertake such activities. Both the European and Japanese programs, however, are being directed toward the development of servicing capability as an integral activity within future manned space programs.

NASA satellite servicing activities are currently internally coordinated through the Office of Space Flight (OSF). NASA's Office of Space Flight is currently developing a Satellite Servicing Management Plan to establish agency policy and provide guidelines for implementation of servicing policy at individual program levels within NASA and other U.S. agencies, in addition to providing for interaction with potential commercial users. In addition, the NASA Satellite Servicing Steering Committee provides coordination between the various NASA offices involved with servicing activities to ensure that the requirements of the various NASA user organizations are being met, and that servicing activities are not being duplicated. The Satellite Servicing Working Group, with representatives from all of the NASA field activities engaged in satellite servicing, periodically reviews the progress on servicing developments which are under way and provides input to NASA Headquarters.

For coordination with external parties involved in satellite servicing activities, NASA relies on two mechanisms. The NASA/DoD On-Orbit Maintenance Working Group established under the Memorandum of Agreement coordinates servicing activities between NASA and the DoD. External satellite servicing coordination is sponsored by the Office of Space Flight through periodic satellite servicing workshops. These workshops are the mechanism by which NASA communicates its servicing progress and future plans to industry and the greater user community.

The most recent of these workshops, the Satellite Servicing Workshop III, was held at Goddard Space Flight Center on June 9-11, 1987. In addition to this comprehensive OSF-sponsored workshop, the NASA Space Station Office hosted robotics demonstrations at Goddard Space Flight Center on June 22-24, 1987 as part of a tour presented in conjunction with the American Institute of Aeronautics and Astronautics (AIAA) Space Station Conference. A total of eight demonstrations of the advanced robotic systems technology being evaluated for use on the Space Station were held for various audiences including AIAA members, Goddard management and employees, and the general public.

NASA activities in these areas ensure that appropriate servicing data is readily available to potential users so that each user may make an educated and informed decision regarding their use of servicing. Tool catalogues and capability documents currently in use are being updated and NASA plans to soon publish revised versions. Ultimately, users will avail themselves of on-orbit servicing when it makes programmatic sense, and each case will be considered individually. NASA will help non-NASA users to understand programmatic tradeoffs and will make available to them, on a cost-reimbursable basis, the general kinds of support and equipment needed.

o The pertinence of satellite servicing to insurance, including the character, cost and availability of insurance.

Present day satellite insurance policies pay the insurer up to a specified value for the total or partial loss of a satellite. Each policy is unique, i.e., a singular agreement between insurer and insured. Coverage provided mandates mitigation of damages in the event of loss and salvage rights in favor of insurers where, in some instances, insurers actually take title to the satellite. Consequently, repair or retrieval is desirable in cases where technically and economically feasible, with the insurers often making the ultimate decision.*

Insurance coverage is available for two separate phases of a satellite's life: launch and on-orbit operation. A leading underwriting institution has stated it would look favorably upon designs for improved repairability and retrievability, but cannot require satellite manufacturers to incorporate these features. Should these capabilities be included, they could produce reductions in insurance premiums for both phases. This could be achieved through the moderation of loss costs associated with possible failures, i.e., reducing what would otherwise be a total loss for an unrepairable and therefore unusable satellite to a partial loss. This would be accomplished by restoring all or a portion of the capability of such a satellite through on-orbit repair or retrieval.

The Palapa and Westar retrievals and the SYNCOM IV-3 on-orbit repair demonstrated to the insurance industry that the capability to service spacecraft in low Earth orbit accessible by Shuttle has been established. Consequently, one underwriter, as a result of this experience, has established in its insurance coverages the following requirement -- that the insured exercise all available means within reason to salvage a satellite that

*This and other information regarding satellite insurance policies throughout Chapter 6 is derived primarily from the office of the Vice President of INTEC (International Technology Underwriters) in Washington, D.C.

has either failed to reach orbit or that has failed in orbit. To the extent Shuttle-based servicing operations were available, insureds could have an increased ability to meet this requirement where satellites are stranded in low Earth orbit, or are capable of being de-orbited to low Earth orbit from a higher orbit. There is no current impact on insurance in the case of geosynchronous satellites or satellites unable to be placed in Shuttle-accessible orbit since transportation for servicing is not yet available.

Proposed serviceable commercial space platforms could greatly impact future insurance coverages. This coverage is unique and subject, moreover, to negotiation between the parties. Certain basic coverages specifically tailored for these platforms are envisioned; for example, property coverage for asset values, liability coverage for damage to third parties, and liability coverage for product malfunctions. These insurance coverages will be related to the types of servicing to be conducted; therefore, their requirements will be specifically tailored to the ultimate use of the facility.

Insurance underwriters, when establishing rates, do analyze the partial loss versus total loss components. This information is calculated in terms of loss failure probabilities and in terms of monetary impact associated with projected failure scenarios. The addition of servicing enhancements can work toward reducing failure probabilities and the associated costs for failures. This would impact both launch insurance coverages to the extent those coverages included satellite initial operations, and on-orbit coverages to the extent the satellites could be accessed.

The insurance issue, it should be noted, does not impact U.S. government spacecraft since all government payloads are self-insuring. The potential for total loss to the Government would be reduced if the spacecraft were serviceable in the event of failure.

o The prices to be charged for satellite servicing such that the full cost of such servicing can be recovered.

In August 1986, President Reagan directed that NASA shall no longer provide launch services for commercial and foreign payloads unless those payloads have unique, specific reasons to be launched aboard Shuttle. Accordingly, the Space Transportation System (STS) will launch only payloads that are Shuttle unique or have national security or foreign policy implications.

NASA may still launch those payloads which conform to the above noted 1986 decision, including the provision of Shuttle-unique services for on-orbit spacecraft. Therefore, a pricing policy both for launching and servicing of commercial and foreign payloads is still a requirement.

NASA's experience to date in pricing satellite servicing for commercial customers consists of the Palapa B-2 and Westar VI retrievals on STS 51-A, the attempted repair of SYNCOM IV-3 on STS 51-D, and its subsequent successful repair on STS 51-I. These satellites had experienced upper stage failures immediately following their deployment from the Shuttle. The charge for Palapa and Westar retrievals totaled $5.5M, and the charge for SYNCOM repair totaled $8.5M. At the time that services were priced for the Palapa, Westar, and SYNCOM satellites, NASA was strongly interested in demonstrating its Shuttle-based servicing capabilities. The servicing charges were determined on an additive cost basis. The costs which were included were those associated with mission planning, development of unique hardware, integration, training, and revisit/retrieval.

A proposed satellite servicing pricing policy presented in the NASA Report to Congress, December 1986, entitled "On-Orbit Service, Repair, and Recovery of Spacecraft Report," was based on pre-51-L STS data. This policy contains three costing elements: transportation, a tailored package of services, and additional optional services. This pricing policy was based on full cost recovery and included pro rata costs of transportation, the costs of using any servicing tools and capabilities (such as EVA, MMUs, OMVs, etc.), and the costs of any non-standard optional services, including the full, rather than additive, costs of any mission-unique hardware. Satellite servicing missions priced on a full cost recovery basis, will result in prices exceeding those charged for the prototype repair missions on STS 51-A, D, and I.

Previous pricing algorithms for Shuttle services, including satellite servicing, used factors which have changed significantly over the past two years. The two primary factors which will affect future Shuttle pricing are: a projected Shuttle flight rate which is reduced from earlier projections, and a recently announced and significant increase in downweight capability of the orbiter. Because Shuttle flight cost is a major element in pricing a retrieval mission, the current retrieval/revisit pricing policy is being reformulated to reflect these changes.

Policy has not yet been established for pricing of Space Station supplied servicing. It is NASA's intent, in accordance with the civil space policy, to seek full cost recovery for pricing of Shuttle servicing.

Chapter 8: Goals and Objectives

*o "The Administrator shall conduct a thorough and comprehensive study of satellite servicing with a view toward establishing national goals and objectives for utilizing such capabilities."**

Satellite servicing is a technologically evolving activity which has not yet attained final stages of development. Progressing from a contingency reaction to a baselined activity within many user programs, the intent of servicing is to extend operational life, enhance capabilities, and decrease system life-cycle costs. Servicing is currently constrained to Shuttle accessible orbits, but it will evolve to include Space Station based activities and remote operations with robots in support of permanent long-term operations in space. Developments are proceeding rapidly in the international arena; for example, (1) the Federal Republic of Germany will demonstrate robotic operations on an upcoming Spacelab flight; (2) Canada is developing the technology for a Mobile Servicing Center on the Station; and (3) Japan is developing the technology for remote servicing from expendable launch vehicles.

In keeping with the information noted above, NASA proposes that the development of appropriate satellite servicing capabilities to enhance and protect national capital investments in space systems be considered and subsequently adopted as a national goal. With this in mind, NASA presents the following agency objectives for utilizing satellite servicing:

(1) To develop the technology, hardware, tools, facilities, and infrastructure to meet projected NASA servicing requirements;

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*Excerpted from the National Aeronautics and Space Administration Authorization Act of 1988, (H.R. 2782), Title 1, Sec. 118.

(2) To continue to strive towards efficiency (cost-effectiveness) in on-orbit servicing support through the development of general purpose tools and common systems and subsystems;

(3) To continue to evolve on-orbit servicing capabilities, including development of telerobotic and robotic servicing systems, to support servicing at remote sites;

(4) To support servicing needs of DoD, domestic commercial, and foreign space communities upon appropriate request;

(5) To promote the spinoff of commercial services;

(6) To develop and promote the use of servicing interface standards;

(7) To stimulate the technology base in universities and industry; and

(8) To utilize commercially available on-orbit servicing to the fullest extent feasible, and avoid actions that may preclude or deter commercial space sector activities except as required by national security or public safety.

APPENDIX A

OSSA PAYLOADS

This appendix presents a compilation of on-orbit servicing information concerning payloads selected by OSSA as potential drivers for the establishment of servicing requirements at the Space Station. The data was extracted from "OSSA Space Station Servicing Book II", published on November 30, 1987. The information is presented in two summary tables.

Table A-1, "OSSA Payload Summary," lists the payload by abbreviation. The full name of each payload is provided within a column which also includes a brief description of the payload. A summary of the servicing activities for the payload appears in the last column. The second column indicates whether the payload is on attached payload (A), a free-flyer (FF), a polar platform (P), a co-orbiting platform (C), or a laboratory module (L).

As a rough measure of the degree of payload definition, the current phase of development of each payload is indicated in column 3. The categories are Pre-phase A (Pre-A), Phase A, Phase B, and Phase C/D. Pre-phase A is the conceptual study phase in which requirements documents are produced identifying scientific objectives, technical concepts, and preliminary scoping. Phase A involves analysis of alternative system designs, preparation of a preliminary project plan, and feasibility studies. Phase B encompasses preliminary design and verification of critical systems and subsystems, and concludes with the choice of a single project approach and the development of a detailed schedule and procurement approach. Phase C/D refers to a stage where developmental funding as been approved and implemented.

The second table, "OSSA Payload Milestone and Servicing Schedule," shows the launch date, the date of first Space Station service, the servicing interval in months, and the expected operational lifetime of the payload. The shaded bars in the launch date column represent a time interval during which the payload is operational, and the leftmost border of the shaded bar falls in the year of launch.

OSSA PAYLOAD SUMMARY

PAYLOAD	TYPE	PHASE	DESCRIPTION	SERVICING
ASTRO	A	C/D	ASTRO applies ultraviolet imagery, spectroscopy & polarimetry to the study of faint objects.	None
ASTROMAG	A	PRE-A	Astrophysics Magnet Facility. Uses superconducting magnet for high energy Astrophysics.	*On-Orbit Assembly *Resupply Helium *Replace Science Instruments
ATF	A	PRE-A	Astrometric Telescope Facility. Optical telescope designed to search for planetary systems & support additional Astrophysics.	*On-Orbit Assembly *Replace Mechanical or Electronic Components
AXAF	FF	B	Advanced X-Ray Astrophysics Facility. The X-Ray Great Observatory.	*Changeout ORUs and Science Instruments
CDCE	A	A	Cosmic Dust Collection Experiment. Measures orbital parameters of impacting extraterrestrial material.	*Changeout Impacted Cells
CRNE	A	C/D	Cosmic Ray Nuclei Experiment. Studies energy spectra and propagation of Cosmic Rays. Electronic Counter Telescope.	None
Eos	P	A	Earth Observing System. Obtains detailed physical, chemical, & biological studies of earth & atmosphere through four polar platforms.	*ORU Changeout *Science Instrument Replacement
EP	FF	C/D	Explorer Platforms. Will carry various instrument packages to perform Astrophysics studies of a wide variety of objects.	*Changeout Science Instrument. First exchange is XTE for EUVE
GRO	FF	C/D	Gamma Ray Observatory. This Great Observatory will study gamma ray emitting objects.	*Replace 1000 kg of Hydrazine
HH/ERBE	A	PRE-A	Hitchhiker Earth Radiation Budget Experiment. Hitchhikers allow small science and engineering payloads to conduct their intended missions. ERBE investigates radiative output of the tropics over time.	None
HRSO	A	PRE-A	High Resolution Solar Observatory. Addresses fundamental solar phenomena.	*Replace co-observing ultraviolet science instrument
HST	FF	C/D	Hubble Space Telescope. This visible light Great Observatory will allow study of objects up to 14 billion light years away.	*Changeout ORUs *Science Instrument Replacement
LAMAR	A	B	Large Area Modular Array. Performs sensitive cosmic x-ray observations in the 0.10 - 10.0 KEV energy range.	*Replace gas module.
LASERCOM	A	PRE-A	Laser Communications Engineering Test. Tests acquisition and tracking with telescope, transmitter, and receiver.	None
LAWS	A	A	Laser Atmospheric Wind Sounder. Provides a direct measurement of the tropospheric wind field, via Doppler-LIDAR Techniques.	*Changeout of ORUs

OSSA PAYLOAD SUMMARY (continued)

PAYLOAD	TYPE	PHASE	DESCRIPTION	SERVICING
LDR	FF	PRE-A	Large Deployable Reflector. Will conduct submillimiter-infrared astronomical observation of various astrophysical phenomena in the 30 - 1000 micron region.	*On-orbit assembly *Replenish liquid helium
LSRF	L	A	Life Sciences Research Facility. Pressurized module which will provide a laboratory in space for basic research in the Life Sciences.	*Resupply of consumables and removable of waste
MMPF	L	A	Microgravity & Material Processing Facility Pressurized module which provides opportunities to process very pure & new forms of materials in a controlled microgravity environment.	*Resupply of consumables and removable of waste
PIMS	A	A	Plasma Interaction Monitoring System. Measures induced space environment around the Space Station and the interactive effects between the Space Station and this enivronment.	None
POF	A	A	Pinhole Occulter Facility. Uses x-ray & corna-graph equipment to study plasma dynamics.	*Changeout two proportional counters
SBAR	A + FF	PRE-A	Space-Based Antenna Range. Will test experimental communications links, antenna characteristics, & other functions of spacecraft prior to final orbit placement.	*Changeout test instrument & subsystem modules *Replenishment of hydrazine
SIRTF	FF	A	Space Infrared Telescope Facility. This Great Observatory will study astrophysical features / phenomena in the infrared region.	*Resupply liquid helium *Replace ORUs
SRI	A	PRE-A	Search and Rescue Instruments	*TBD
3S	FF	PRE-A	Space Station Spartan. This system is a relatively low cost system which allows free flying missions to originate from SS.	*Changeout of science Instrument *Replenish hydrazine *Changeout ORUs
STO / PIG	A + FF	A	Solar Terrestrial Observatory: Plasma Instrument Group. See STO / SS.	*Replace ORUs Replenish Gas
STO / POP	P	A	Solar Terrestrial Observatory: Polar Orbiting Platform. See STO / SS.	*Replace ORUs Replenish Gas
STO / SIG	A + FF	A	Solar Terrestrial Observatory: Solar Instrument Group. See STO / SS.	*Replace ORUs *Replace film cannisters
STO / SS	A + FF	A	Solar Terrestrial Observatory: Space Station. Has a variety of instruments to study solar activity & the physical processes coupling the atmosphere, the magnetosphere, & the sun.	*Changeout ORU's *Replace Film
TRIS	A	A	Tropical Region Imaging Spectrometer. Studies biological & physical processes of tropical regions	*Replace ORUs (cooling system)
TRMM	A	A	Tropical Rainfall Measurement Mission. Measures rain-fall in the tropics to increase our understanding of tropical energetic & hydrologic processes.	None
XGP	FF	PRE-A	Experimental GEO Platform. Allows development & demonstration of enabling communications & science payload & antenna technologies.	*Unfurl & test XGP at SS *Replenish hydrazine (in SITU) *Replace ORUs (in Situ)

A = Attached; C = Co-orbiting Platform; FF = Free-Flyer;
L = Laboratory; P = Polar Platform

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Table A-2: OSSA PAYLOAD MILESTONE AND SERVICING SCHEDULE

PAYLOAD	LAUNCH DATE (89–01)	DATE OF FIRST SERVICE 89	90	91	92	93	94	95	96	97	98	99	00	01	SERVICING INTERVAL (MTHS) STS	SS	OPERATIONAL LIFETIME (YRS)
ASTRO	TBD	N/A													N/A		1
ASTROMAG									●							12 - 24	6 - 8
ATF									●							60	20
AXAF											●					30 - 60	15
CDCE								●								6	5
CRNE		N/A													N/A		2
EOS / NPOP-1											●				36/PLATFORM		15 / PLATFORM
EOS / NPOP-2													●		36/PLATFORM		15 / PLATFORM
EP						●									24	24	10
GRO	WITH REBOOST						●									48	4 / 8
HH/ERBE		N/A													N/A		5
HRSO	TBD	TBD														12	3
HST					●										36	18 - 22	15
LAMAR	TBD	LIFT OFF + 3 YEARS														36	TBD
LASERCOM		N/A													N/A		1/2 - 1
LAWS														●		36	5
LDR													●			24	15
LSRF								●								3	20 - 30
MMPF								●								1, 3	20 - 30
PIMS	TBD	N/A													N/A		> 5
POF												●				60	15
SBAR	TBD									●						6	INDEFINITE
SIRTF											●					18 FIRST, 27 AFTER	10
SMM RETRIEVAL			●												N/A		N/A
SRI	TBD	TBD													TBD		TBD
3S	TBD								●							4 or 6	TBD
STO / PIG							●									3	4
STO / POP-1								●							1		4
STO / POP-2													●		1		4 - 6
STO-SIG							●									3	4
STO-SS							●									3	4
TRIS	TBD										●					36	TBD
TRMM	TBD	N/A													N/A		3
XGP											●					3	20

*Note: Many of the mid and long term payloads are still in the planning and development stage and have not yet been approved for development. See Table A-1 for the phase of each payload. Source (for all except SMM Retrieval): OSSA Space Station Servicing Data Book II (Nov. 30, 1987).

Indicates approved payload.

APPENDIX B

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APPENDIX C

ACRONYM LIST

AIAA	American Institute of Aeronautics and Astronautics
AXAF	Advanced X-Ray Astrophysics Facility
CCTV	Closed Circuit TV, Voice Controlled
CNDB	Civil Needs Data Base
DoD	Department of Defense
EASE/ACCESS	Experimental Assembly of Structures in EVA/Assembly Concept for Construction of Erectable Structures
ELV	Expendable Launch Vehicles
EOS	Earth Observing System
ESA	European Space Agency
EVA	Extravehicular Activity
FSS	Flight Support System
FTS	Flight Telerobotic System
GRO	Gamma Ray Observatory
GSFC	Goddard Space Flight Center
HST	Hubble Space Telescope
ISF	Industrial Space Facility
IVA	Intravehicular Activity
KSC	John F. Kennedy Space Center
LDEF	Long Duration Exposure Facility
MMS	Multimission Modular Spacecraft
MMU	Manned Maneuvering Unit
MOA	Memorandum of Agreement
MSC	Mobile Servicing Center
MSFC	George C. Marshall Space Flight Center
MST	Module Service Tool
MTFF	Man-Tended Free Flyer
NASA	National Aeronautics and Space Administration
NSDD	National Security Decision Directive
OMV	Orbital Maneuvering Vehicle
ORU	Orbital Replacement Unit
OSF	Office of Space Flight

OSSA	Office of Space Science and Applications
OTV	Orbital Transfer Vehicle
PAM	Payload Assist Module
PMC	Permanently Manned Capability
POP	Polar Orbiting Platform
RMS	Remote Manipulator System
SAMSS	Space Assembly, Maintenance, and Servicing Study
SFU	Space Flyer Unit
SHOOT	Superfluid Helium On-Orbit Transfer
SIC	Standard Interface Connectors
SIRTF	Space Infra-Red Telescope Facility
SMM	Solar Maximum Mission
SPDM	Special Purpose Dexterous Manipulator
STS	Space Transportation System